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AMS status and results after four years of operations on the ISS

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Summary. — The Alpha Magnetic Spectrometer (AMS) is the major particle physics experiment in space. In its first four years in orbit, on the International Space Station (ISS), AMS has collected more than 60 billion cosmic ray events up to multi-TeV energies. Status and results will be presented.

1. – Introduction

AMS is a general purpose high-energy particle physics detector. It was installed on the International Space Station (ISS) on May 19th, 2011, to conduct a unique long-duration mission (up to 20 years) of fundamental physics research in space. The main physics objectives of AMS are the search for antimatter, dark matter, and the origin of cosmic rays thanks to the precision measurements of flux and energy spectra of charged cosmic rays in space.

2. – The AMS Detector

The AMS detector, which measures $3 \times 4 \times 5$ cubic meters and weighs 7.5 tonnes, is a state-of-the-art particle physics detector designed to operate as an external module of the ISS. The AMS electronics consists of 650 microprocessors and about 300000 readout channels; the total power consumption is less than 2.5 kW and on-board data processing reduces the raw data volume by a factor of 1000 without the loss of physics information. The collected data are down linked to the ground at an average rate of 10 Mbit/s. On the ISS, the particle rates in the acceptance vary from 200 Hz near the equator to about 2000 Hz near geomagnetic poles. AMS operates without interruption and is monitored continuously from the ground, detector performance is steady over time.

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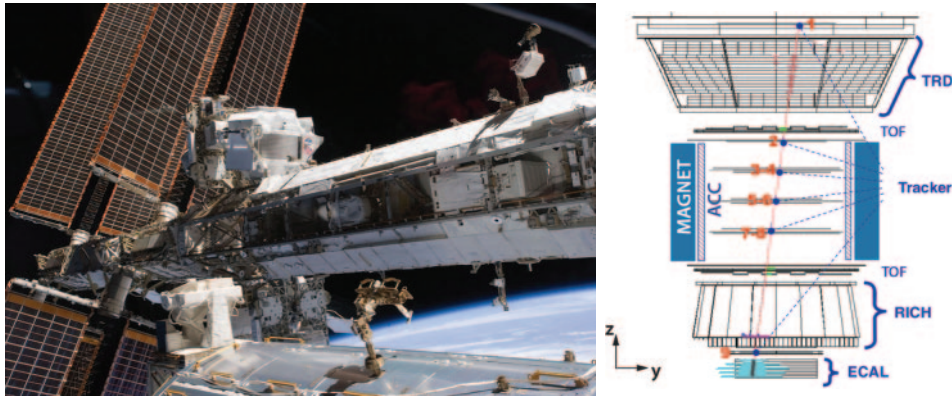


Fig. 1. – Photo by NASA: AMS installed on the ISS (left). A 1.03 TeV electron event as measured by AMS on ISS in the bending (y - z) plane (right).

The layout of the AMS-02 detector is shown in fig. 1. AMS consists of nine planes of the precision silicon tracker, a transition radiation detector (TRD), four planes of time of flight counters (TOF), a 0.14 T permanent magnet, an array of anticoincidence counters (ACC) surrounding the inner tracker, a ring imaging Cherenkov detector (RICH), and a 17 radiation length electromagnetic calorimeter (ECAL). The figure also shows an event of a high-energy electron of 1.03 TeV recorded by AMS on ISS [1]. The tracker coordinate resolution is $10\ \mu\text{m}$ ($7\ \mu\text{m}$) for $Z = 1$ ($Z = 2$) particles, this allows a maximum detectable rigidity (p/Z) of $\sim 2\ \text{TV}$ for protons and $\sim 3.2\ \text{TV}$ for helium.

The redundancy of the different sub-detector measurements ensures an excellent particle identification. In particular: the silicon tracker planes 1 to 9 measure the particle charge, sign, and momentum. The TRD identifies the particle as e^\pm or proton or higher charge nucleus. The TOF measures the absolute charge value and is used to select downward-going particles. The RICH independently measures the charge and velocity. The ECAL measures the 3D shower profile, independently identifies the particle as an e^\pm and measures its energy. As an example, a positron is selected by

- 1) all redundant charge measurement compatible with $|Z| = 1$,
- 2) positive rigidity in the tracker,
- 3) large transition radiation deposition in the TRD,
- 4) an electromagnetic shower shape in the ECAL,
- 5) the matching of the ECAL shower energy and axis with the momentum measured with the tracker and magnet.

TRD, ECAL, and the silicon tracker are the main detectors that allow a significant reduction of the proton background in the identification of the positron and electron samples. Signals from the 20 TRD layers and 18 ECAL layers are combined in statistical estimators that allow electron/proton separation. Figure 2 shows the typical distributions of the ECAL estimator (left) and TRD classifier (right) for electrons and protons in the AMS data. The proton rejection power of the TRD classifier at 90% electron efficiency measured on orbit is 10^3 – 10^4 in the 2–200 GV rigidity range. The proton rejection

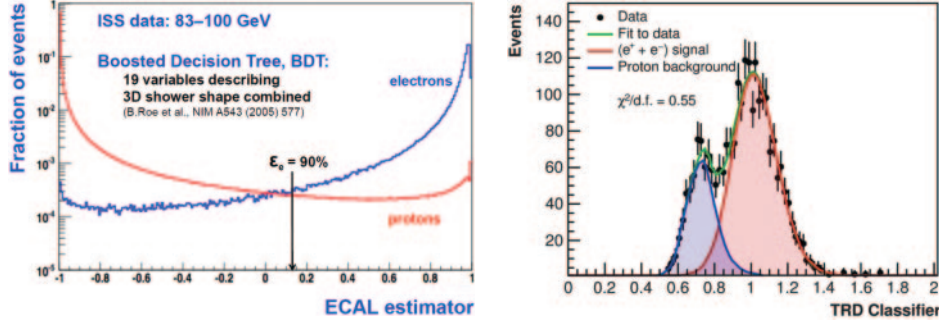


Fig. 2. – Example of AMS electron/proton separation capability. Electron-Proton discrimination capability through 3D shower shape reconstruction in ECAL detector (left). Electron-Proton separation through the amount of transition radiation photons collected by TRD detector for electrons of 150–170 GeV (right).

power of the ECAL estimator, when combined with the energy-momentum matching requirement, reaches 10^3 – 10^4 for rigidity from GV to TV. The performance of both the TRD and ECAL estimators are derived from data taken on the ISS [1-5]. The complete detector was tested at the Super Proton Synchrotron (SPS) at CERN before the launch. In the beam tests, AMS was exposed to the primary 400 GeV proton beam and to secondary beams of positrons and electrons in the momentum range from 10 to 290 GeV and to 10–180 GeV charged pions.

3. – Results on electrons and positrons

AMS has published three important results on positrons and electrons [2-4] in 2014. Among 41 billion primary cosmic ray events, 10 million have been identified as electrons and positrons. AMS has precisely measured the positron fraction, $e^+/(e^+ + e^-)$, in the energy range 0.5 to 500 GeV as shown in fig. 3. The high statistics of AMS measurement allow to precisely determine that the energy at which the fraction starts to quickly increase is 8 GeV. The measurement is extended at higher energy respect to previous results. Figure 3 shows also that the measured positron fraction has no observable sharp structures and ceases to increase, suggesting the presence of a maximum, at 275 ± 32 GeV. This is a previously unobserved behavior of the positron fraction and can be related to the characteristics of the source of the excess of positrons in cosmic rays. In particular, among the many interesting models (see, *e.g.*, [6]) two popular classes of interpretations identify the source of e^+ in nearby pulsars or in the contribution due to galactic dark matter annihilation. In this latter case, after flattening out, positron fraction is expected to decrease rapidly with energy due to the finite and specific mass of the dark matter particle, and no dipole anisotropy is expected to be observed. A detailed analysis of the arrival directions of positrons and electrons of AMS data shows that the positron to electron ratio remains consistent with isotropy; the upper limit on the amplitude of the dipole anisotropy is $\delta \leq 0.030$ at the 95% CL for $E > 16$ GeV.

Finally also the single fluxes of positrons up to 500 GeV, electrons up to 700 GeV and the sum flux ($e^+ + e^-$) up to 1 TeV have been measured. Figure 4 left plot shows that the behavior of electrons and positrons fluxes are significantly different from each other both in their magnitude and energy dependence. Neither the electron flux not the positron

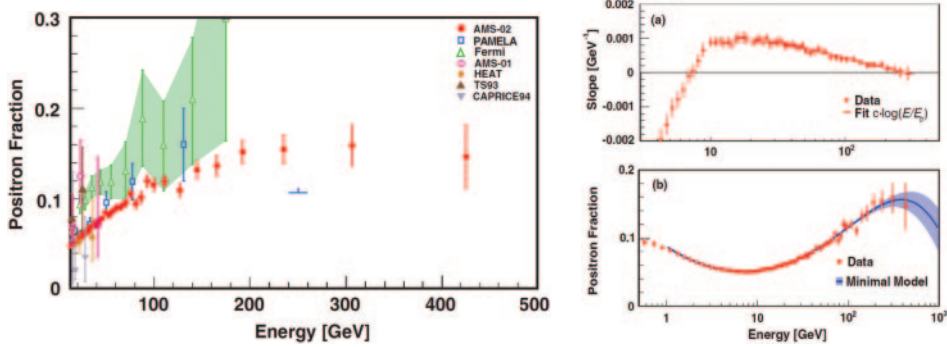


Fig. 3. – Left plot: The positron fraction measured by AMS compared with previous results (see refs. in [2]). The positron fraction measurement extends the energy range to 500 GeV and demonstrates that, above ~ 200 GeV, the positron fraction is no longer increasing. Right plots: (a) The slope of the positron fraction *vs.* energy over the entire energy range. The line is a logarithmic fit to the data above 30 GeV. (b) The positron fraction measured by AMS and the fit of a minimal model (see [2] for details).

flux can be described with a constant spectral index and between 20 and 200 GeV an hardening of the positron flux is observed. This is an important proof that the excess seen in the positron fraction is due to a relative excess of high energy positrons, as expected for example from dark matter collisions, and not the loss of high energy electrons.

Figure 4 right plot shows the combined ($e^+ + e^-$) flux as measured by AMS and compared with previous results. Respect to the separate e^+ and e^- fluxes, this measurement benefits of smaller statistical and systematic errors and the energy range is extended to 1 TeV. The combined ($e^+ + e^-$) flux is smooth and, starting from 30 GeV, can be described by a simple power-law with a constant spectral index.

Thanks to the redundancy of energy/momentum measurements, the AMS ($e^+ + e^-$) flux benefits of an unprecedented precision in the absolute energy scale determination; therefore large deviations from a simple power-law in the energy range 300–800 GeV (suggested by past experiments) can be excluded with high confidence.

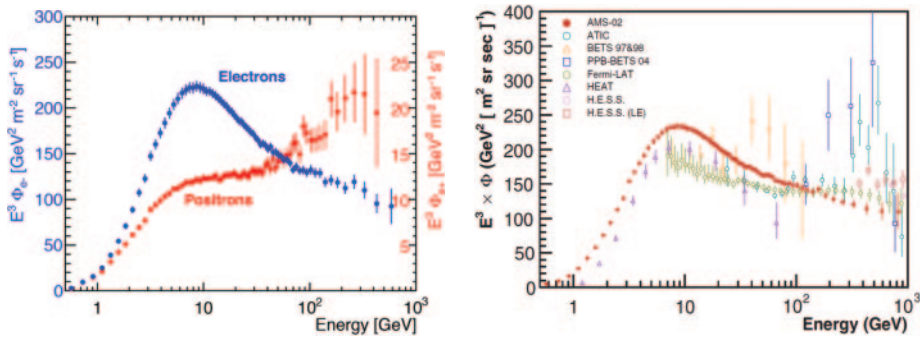


Fig. 4. – Left plot: AMS flux measurement for positrons (red axis scale) and electrons (blue axis scale). Right plot: AMS total ($e^+ + e^-$) flux measurement compared with earlier measurements (see references in [4]). In both plots, fluxes are multiplied by E^3 .

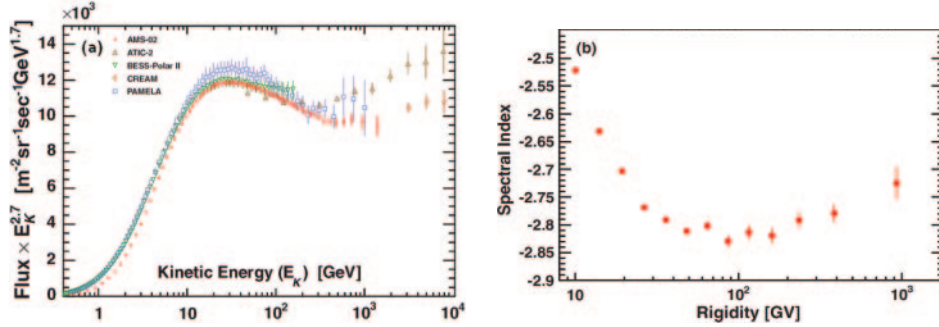


Fig. 5. – (a) The AMS proton flux multiplied by $E_K^{2.7}$ as a function of the kinetic energy E_K and compared with recent measurements (see refs. in [5]). (b) The dependence of the proton flux spectral index γ_p on rigidity R .

4. – Results on protons, anti-protons and nuclei

High precision measurements of proton and nuclear fluxes are important in understanding the origin, acceleration, and propagation of cosmic rays in the galaxy. This information is necessary for the possible interpretation of the positron and anti-proton measurements in terms of dark matter or exotic sources. AMS collaboration has recently published the measurement of the proton flux in primary cosmic rays based on 300 million events [5]. Figure 5(a) shows the measured proton flux compared with recent measurements from other experiments. The proton flux is incompatible with a single power-law and the measured spectral index progressively hardens with proton energy above ~ 100 GeV. In particular, in fig. 5(b) the variation of the measured spectral index $\gamma_p = d[\log(\Phi)]/d[\log(R)]$ as a function of the proton rigidity R is shown.

Anti-proton/proton flux ratio and the cosmic ray nuclear abundances/energy spectra are currently under investigation by AMS [7]. Forthcoming results on nuclei will be able to test with high sensitivity the presence of spectral index change in the different nuclei components up to multi-TeV energy. The anti-proton/proton study from AMS will not only greatly improve the accuracy of the existing measurements up to 180 GeV, but will allow to extend it at higher energy. In particular up to 450 GeV the accuracy of AMS will challenge the current theoretical uncertainties in the background expected for anti-proton/proton flux ratio.

These new observations provide important information on the understanding of cosmic ray production and propagation. The accuracy and characteristics of the data, simultaneously from many different types of cosmic rays, require a comprehensive model to ascertain if their origin is from dark matter, astrophysical sources, acceleration mechanisms or a combination of sources.

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